SYNOPSIS
Integration of Urban Forms, Society and Governance in Planning Solar Cities of India

Radhika Bhanja
Registration No.: R-17RS12210089
Working under the supervision of Dr. Koel Roychowdhury

Background

Energy plays a crucial role in accelerating and strengthening the economic and social development of nations (Dias, Mattos, & Balestieri, 2006; Martinez & Ebenhack, 2008). It is required in all sectors of the economy including residential, commercial industrial, transport, infrastructure development, distribution of social and economic services, and food production. The increase in energy consumption in cities has multiplied rapidly in the past few decades (de Oliveira & Oliveira, 2018), often leading to a decline in fossil-fuel based energy sources and the consequent adoption of renewable energy resources. The transformation of the energy system to non-conventional sources of energy is no more limited to remote locations of countries and islands, but also in the urban centres. Integration of such complex systems into the electricity generation and distribution framework requires flexibility to adopt new technologies, affordability, reliability, and continuous monitoring of new additions to the system. For sustainable transformation in the energy system, the inclusion of renewable energy, mostly in the form of a hybrid mode of the energy supply system, is capable of low carbon growth (Schmidt et al., 2016), green economy, efficient electricity markets (Muñoz et al., 2021), better resource management to shorten the demand-supply gap (Vossier et al., 2018), and cost-effective approaches to the system (Liu et al., 2019), resulting into refined and efficient policies derived from such archetypes to optimize energy usage across cities. Bagheri et al. (2019) empirically established that the integration of low emission power plants combined with solar, or wind system can reduce the cost of electricity by upto 30% of the existing prices when the electricity is generated from the power plants entirely. In Asian cities, urban electricity consumption through solar photovoltaics (PVs) is more frequent and remunerative than energy generated from wind energy and urban waste (Kammen & Sunter, 2016).

Numerous studies have explored the relationship between energy consumption, urbanization, and economic growth at the national level. Many factors influence the energy demand of a nation; some of them being population and economic growth, the efficiency of energy use, urbanization, industrial growth, energy pricing, availability of energy resources, and the environmental problems associated with it (Pachauri & Jiang, 2008; Reddy Sudhakara & Balachandra, 2003; Satterthwaite, 2009; S. Wang et al., 2016). Similarly, the drivers of energy generation and consumption in megacities of the world are characterized by high per capita electricity use, economic growth, high built-up density, transportation, water consumption and waste generation (Athanassiadis et al., 2017; Kennedy et al., 2015). Indian cities are characterized by high energy consumption and contribute significantly to greenhouse gas emissions (Mitra et al., 2003). In the current period, the operation of cities cannot be solely dependent on renewable resources, rather a combination of electricity generated from both thermal and green energy will suffice to sustain the growing demands of the cities unconditionally. Solar energy is one of the key renewable energy resources where large-scale implementation of solar projects can ensure a net zero future in cities and rural areas. In the case of India, the potential to generate solar energy is about 6 billion GWh of energy annually, which is the highest among the energy generating potential of other renewable sources (Tripathi et al., 2016). National solar projects in India date back to the 1970s, during the world oil crisis when India decided to be independent of oil imports and switch to renewable energy. Therefore, new Research and Development teams were formed to design solar cells, ensuring the capacity to develop and manufacture solar photovoltaics (SPVs), and strengthen the economy to provide incentives for the installation of SPVs in the country. Over time, India has strengthened their manufacturing base and production performance to generate 48212.20 MU by 2020 (CEA, 2021) and has achieved fifth rank globally in solar power generation and deployment,

surpassing Italy, Australia, and the United Kingdom (MNRE, 2022). Thus, solar technology coupled with the existing electricity distribution system will help in enhancing the sustainability of the electricity generation and distribution system of India.

In order to understand the implications of energy use on sustainable development in cities, it is necessary for urban planners and policy-makers to define an integrated energy planning strategy by taking into account the complex relationship of energy and resource flows in the city, the role of government and non-government organizations in promoting renewable-friendly planning systems and the market along with the spatial configuration of the city. To acknowledge the Paris Agreement at COP21 and Goal 7 of Sustainable Development Goals, India has embarked on promoting sustainable low carbon futures for its citizens by launching an ambitious project of installing 175 GW of renewable energy by 2022 where 100 GW of power will be generated from solar energy (PIB, 2018). India has launched many schemes and programs to fulfill its green energy missions of India. The Solar City Mission (SCM) program is one of the initiatives taken by the Ministry of New and Renewable Energy (MNRE), launched in 2015, to fulfill the energy demands of cities. The objective of the scheme is to minimize 10% of the projected demand for non-renewable energy in the cities at the end of five years, through its combination with green energy sources. The programme aims to promote the use of renewable energy in urban areas by providing support to Municipal Corporations for the preparation and implementation of a road map to develop their cities as solar cities. In order to prevent the cities from slowing down the implementation of the master plans (Ministry of New and Renewable Energy, 2018), the urban planners must quantify the relationship between energy resources and variables that promote green development of the city. This research tries to ascertain the factors which promote solar city planning in India, through the assessment of the technical and economic potential of the cities to harness solar energy with respect to the city's electricity generation, combined with society's approach towards green energy adoption and consumption and influence of decentralization of decision making in Government bodies.

Research Gaps

The transition to renewables across the entire urban energy landscape requires planners to estimate whether the cityscape and its dwellers are primed and equipped to adopt the new technologies willingly. Renewable energy can be harnessed either at power stations and supplied via grid connections or at communities for self-consumption. To supply green energy to cities, the urban form of cities and their potential to harness renewable energies need to be explored (Cheng et al., 2006; Steemers, 2003). Identification of energy potential sites for cities usually consider meteorological and geographic data (Fadare, 2009), built environments (Ratti et al., 2005; B. Wang et al., 2017), thermodynamic parameters (Balocco & Grazzini, 2000; Dincer & Rosen, 2005), optimization of power distribution systems (Amado & Poggi, 2013); but for a system to be sustainable, a confluence of technology, consistencies of policies and willingness to pay by the consumers form important aspects in determining the longevity of the energy planning systems. This study explores how a cityscape can determine its sustainable energy consumption pattern and the effectiveness of urban local bodies to escalate the efficiency of energy in these cities. Considering the role of these stakeholders as a major driving force in shaping the future of cities, the study attempts to delineate potential zones within cities where renewable energy based projects can be practised. In order to propose such potential sites of renewable energy development in cities, few research gaps were encountered, such as

1. The capability of Indian cities to embrace the transition to green technologies has been rarely addressed.
2. Cities of developed nations compare experiences and the best practices of other municipalities and territories as an inspiration to design new schemes and policies for local energy planning. Such research is not yet conducted in the Indian context.
3. Solar energy poses significant challenges in the form of citizen interests, where consumer awareness and market acceptance are rarely included in models estimating renewable energy generation potential in cities.
4. No studies has explored the potential to harness solar energy from solar utility plants (solar farms) in and/or around the city boundaries.

Thus, the three research questions that are formulated from the mentioned research gaps are as follows:

1. Which factors determine the viability of planning the solar cities of India?
2. How do the implementation and effectiveness of long-term local energy plans vary across different proposed solar cities in India?
3. Which sites are suitable to practice renewable energy based projects in a proposed solar city where the energy master plan has still not been compiled?

Research objectives

The study is novel in its approach as it provides an integrated approach to quantify regions with a reliable renewable energy market, as empirically investigated from a myriad of datasets, involving secondary sources and primary data such as direct observations of plan implementations in different municipalities, consumer behaviour and city's morphology to welcome new technological advancements in energy sustainability. Thus, the objectives of my research can be summarized as:

1. To identify the key driving factors of sustainability and energy efficiency of the solar cities of India which contribute to the viability of Solar Cities Missions in these cities.
2. To examine the effectiveness of local energy planning processes in major proposed solar cities of India.
3. To delineate suitable sites in a city with:
    a. An energy master plan, to identify any other suitable sites can be allocated for solar projects.
    b. No energy master plan, to identify all suitable sites that can be allocated for solar projects.

Study area

The current research was initiated by considering the 56 solar cities of India. The initial evaluation examines the feasibility of implementing SCM in these cities and ranks them according to their performance in different indicators as mentioned in the Methods section. The cities are distributed throughout India, with a majority of them situated in the western half of India. Maharashtra, Madhya Pradesh, Rajasthan and Uttar Pradesh have a majority of their cities participating in the Solar Cities Mission (SCM) Programme. The capital cities of the seven sister states of northeast India have also participated in this mission. New Town, Haora, Madhyamgram and Bhubaneswar represent the eastern zone in this mission. A few coastal cities of Goa, Kerala, and Tamil Nadu have been selected to carry out this mission. In the second stage, five cities were selected from the results of the first objective to inquire about and examine the second objective of the research which seeks to understand the effectiveness of local energy planning processes in major proposed solar cities of India. The cities consist of NDMC, Ludhiana, Bhubaneswar, New Town, and Haora. Among these cities, three cities have designed their Solar Cities Master Plans from the funds received by the MNRE and have implemented a few projects from their designed plans. The detailed observations from these studies help in determining the final city which lacks a solar city Master Plan and needs inputs to design effective strategies to delineate suitable sites to practise renewable energy based projects within the city premises. The final study area selected to fulfil the third objective of the research is New Town and Haora city of West Bengal.

Datasets and Method

Objective 1: Key drivers of solar city planning

To identify the key drivers of solar city planning, three indices were designed to evaluate which factors contribute majorly to solar city planning. The indices are Techno-economic feasibility of solar city planning, Electricity System Sustainability Index, and City Sustainability Index. While calculating the Techno-economic feasibility of solar city planning, meteorological indicators and economic indicators promoting solar system functioning were considered (Table 1). In case of the Electricity System Sustainability Index (ESSI), 16 consistent indicators that give an account of the energy efficiency of the Indian electricity system were selected. Meanwhile, 12 indicators were considered to calculate the City Sustainability Index (CSI) of Indian solar cities (Table 2). These indicators were normalized using

minimum-maximum method and then aggregated using TOPSIS method. The TOPSIS method was first introduced by Hwang & Yoon (1981). The method assumes that each criterion moves towards a better or poorer utility, which helps in determining the positive and negative ideal solutions. This Multiple Criteria Decision Making model (MCDM) was used because it is used to get the optimum combination of process parameters, thus enabling us to identify which indicators are most feasible for solar city planning. The indicators were combined using Grey Relational Analysis (GRA) method. The GRA method was introduced in 1982 by Ju Long. The "Grey" system proposition establishes a connection between black with white. Grey Relational Analysis uses Grey Relational grade to measure the relation degree of factors. A major advantage of this technique is to find the possible interaction between the various indices and find the significant factor in that process (Girish et al., 2019). The method followed is described in figure 1.

Table 1: Indicators selected for Techno-economic Feasibility of Solar Energy Systems

1	Technical Feasibility of Solar Energy Systems	Units
GHI	Global horizontal irradiation	kWh/m^2
DNI	Direct normal irradiation	kWh/m^3
PVOUT	Photovoltaic power potential	kWh/kWp
2	Economic Feasibility of Solar Energy Systems	Units
TE1	Number of eligible producers stated in policy	Numbers
TE2	Provision of land allotment in policy	Binary
TE3	Number of economic benefits to be provided to the producers as stated in policy	Numbers
TE4	LCOE of solar panel installation in cities	INR

Table 2: Indicators selected for City Sustainability Index and Electricity System Sustainability Index

City Sustainability Index (CSI)			
A	Social aspects of CSI	Sub indicators	Units
1	Built-up structure	Permanent structure of the house; Material of roof is concrete; Material of wall is concrete	%
2	Fulfilment of basic amenities of city households	Own house; Tap water from treated source; Tap water within premise; Household with flush/ pour flush latrine	%
3	Social assets and capabilities of city households	Has kitchen inside house; LPG used as cooking fuel; Household possesses television; Household possesses mobile; Household possesses computer; Household possesses computer without internet connection	%
4	Household lighting facilities	Main source of lighting is electricity; Main source of lighting is kerosene; Main source of lighting is solar energy; Main source of lighting is other oil	%
5	Households possessing different	Household possesses bicycle; two-wheeler; four-wheeler	%

	transport facilities		
6	Social amenities present in the city	Total number of education facilities ; Total number of electricity connections ; Total number of banking facility per 1000 population;Total number of hospitals per 1000 population; Total number of doctors per 1000 population	%
B	Economic aspects of CSI	GDP per capita; Literacy Rate; Working population in the city	%
C	Environmental aspects of CSI	Carbon dioxide emissions per capita	Kg/population
Electricity System Sustainability Index (ESSI)			
1	Social Aspects of ESSI	Change in number of domestic connections; industrial connections; commercial connections; street lighting connections; other connections;	%
2	Affordability Aspect of ESSI	Cost of domestic, commercial and industrial connections	INR
3	Economic Aspects of ESSI	Net electricity available for supply per capita	MW/POP
		Economic productivity (total energy produced / GDP)	MU/INR (in lakh crore)
		Total sales of the electricity utility company / capita	MU/POP
		Aggregate Technical & Commercial losses	%
		Transmission and Distribution Losses	%
		Peak deficit	%
5	Environmental Aspects of ESSI	Renewable energy generation capacity; Solar energy generation potential	%

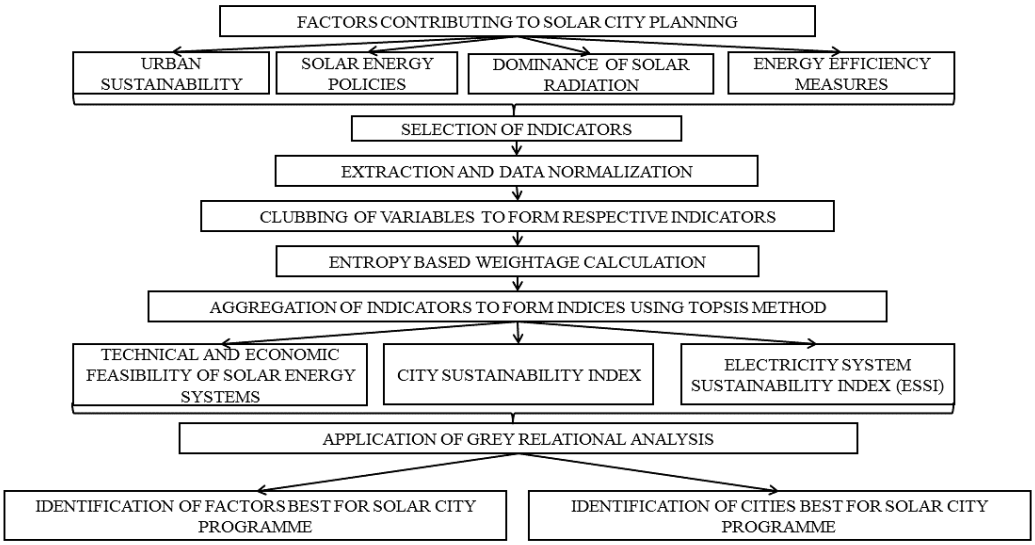
FACTORS CONTRIBUTING TO SOLAR CITY PLANNING
URBAN SUSTAINABILITY
SOLAR ENERGY POLICIES
DOMINANCE OF SOLAR RADIATION
ENERGY EFFICIENCY MEASURES
SELECTION OF INDICATORS
EXTRACTION AND DATA NORMALIZATION
CLUBBING OF VARIABLES TO FORM RESPECTIVE INDICATORS
ENTROPY BASED WEIGHTAGE CALCULATION
AGGREGATION OF INDICATORS TO FORM INDICES USING TOPSIS METHOD
TECHNICAL AND ECONOMIC FEASIBILITY OF SOLAR ENERGY SYSTEMS
CITY SUSTAINABILITY INDEX
ELECTRICITY SYSTEM SUSTAINABILITY INDEX (ESSI)
APPLICATION OF GREY RELATIONAL ANALYSIS
IDENTIFICATION OF FACTORS BEST FOR SOLAR CITY PROGRAMME
IDENTIFICATION OF CITIES BEST FOR SOLAR CITY PROGRAMME

Figure 1: Method followed for 1st objective.

Objective 2: Local energy Master Plans in Solar City Planning

A Total interpretive structural modelling technique (TISM) was used to identify the parameters necessary to design master plan and carrying out local energy planning processes efficiently. TISM analyses the complex hierarchical inter-relationships among all the selected factors. It develops a hierarchical model through multiple pairwise comparisons using Interpretative Structural Modelling technique proposed by Warfield in 1974. It's a type of interpretative modelling to establish a contextual relationship between numerous elements constituting the system and the relationship between variables are scrutinized by the judgements of the group. TISM modelling was conducted as follows: identifying the factors to cover the scope of the problem, formation of a structural self-interaction matrix (SSIM) illustrating pairwise relationships among selected factors based on expert opinion or survey method, from the SSIM, a reachability matrix (RM) is developed. The transitivity must be checked, if any. After perform level partitioning on RM, a conical matrix is generated, which leads to the construction of a hierarchical TISM digraph. Nodes represent the factors and links represent the interpretation relations. The inputs of 17 experts from different domains of energy management were consulted to provide their opinions on the relative importance of each indicator with respect to the other (Figure 2).

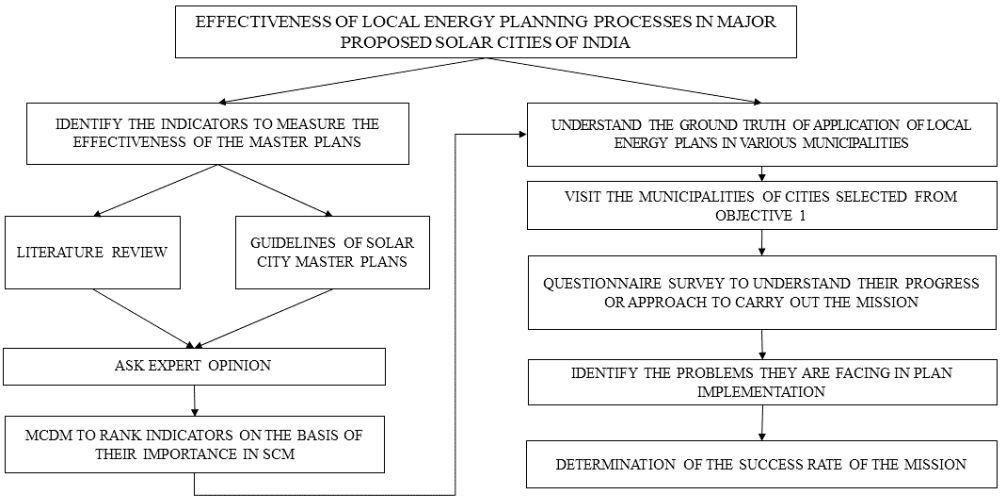
EFFECTIVENESS OF LOCAL ENERGY PLANNING PROCESSES IN MAJOR PROPOSED SOLAR CITIES OF INDIA
IDENTIFY THE INDICATORS TO MEASURE THE EFFECTIVENESS OF THE MASTER PLANS
LITERATURE REVIEW
GUIDELINES OF SOLAR CITY MASTER PLANS
ASK EXPERT OPINION
MCDM TO RANK INDICATORS ON THE BASIS OF THEIR IMPORTANCE IN SCM
UNDERSTAND THE GROUND TRUTH OF APPLICATION OF LOCAL ENERGY PLANS IN VARIOUS MUNICIPALITIES
VISIT THE MUNICIPALITIES OF CITIES SELECTED FROM OBJECTIVE 1
QUESTIONNAIRE SURVEY TO UNDERSTAND THEIR PROGRESS OR APPROACH TO CARRY OUT THE MISSION
IDENTIFY THE PROBLEMS THEY ARE FACING IN PLAN IMPLEMENTATION
DETERMINATION OF THE SUCCESS RATE OF THE MISSION

Figure 2: Method followed for 2nd objective

In the second stage, five cities, New Delhi Municipal Corporation (NDMC), Haora, Ludhiana, Bhubaneswar and New Town were visited, and a primary survey was conducted on the approach and willingness to invest in solar energy technology by the Municipality and their respective solar city cells in their city premise from the Solar City project scheme. Questions which were asked to the representatives of SCM in the Municipalities are related to their solar cell, how the municipality is promoting and implementing the mission, whether they have proper information about the city's current condition regarding energy practises, how they are supporting public-private partnership, whether they are allowing third party power purchasing or incentives to the consumers, and about the GRIHA code.

Objective 3: Delineation of suitable sites for promoting solar energy projects

A site suitability analysis was performed to delineate locations feasible for small scale utility solar parks in and near New Town and Haora city. The solar irradiation datasets are essential to understand whether a region is suitable to harness solar energy throughout the year. Global Horizontal Irradiation (GHI) and Direct Normal Irradiance (DNI) are two such indicators to explain the variation in solar irradiation of a region. Sentinel 2B images were used to classify and extract land cover of the study area. The slope of the terrain was derived from Shuttle Radar Topography Mission (SRTM) digital elevation model with 1 arc-second spatial resolution. Further, two important variables that contribute to the decision making of allocation of land for solar farms are distance of the given location from road and power substations. In order to find suitable locations for setting up solar farms, an GIS based suitability

analysis was performed and the importance of the criterions were determined using a MCDM technique – Analytical Hierarchical Process. The method involves acquisition of secondary data as mentioned above, followed by a questionnaire survey to obtain expert's opinion and views regarding the importance of the criteria to evaluate the main deciding factors in land and resource allocation to set up solar farms in and around HMC. Finally, a weighted overlay site suitability analysis was performed to identify the best, moderate and worst locations to plan solar farm planning in the selected area of interest.

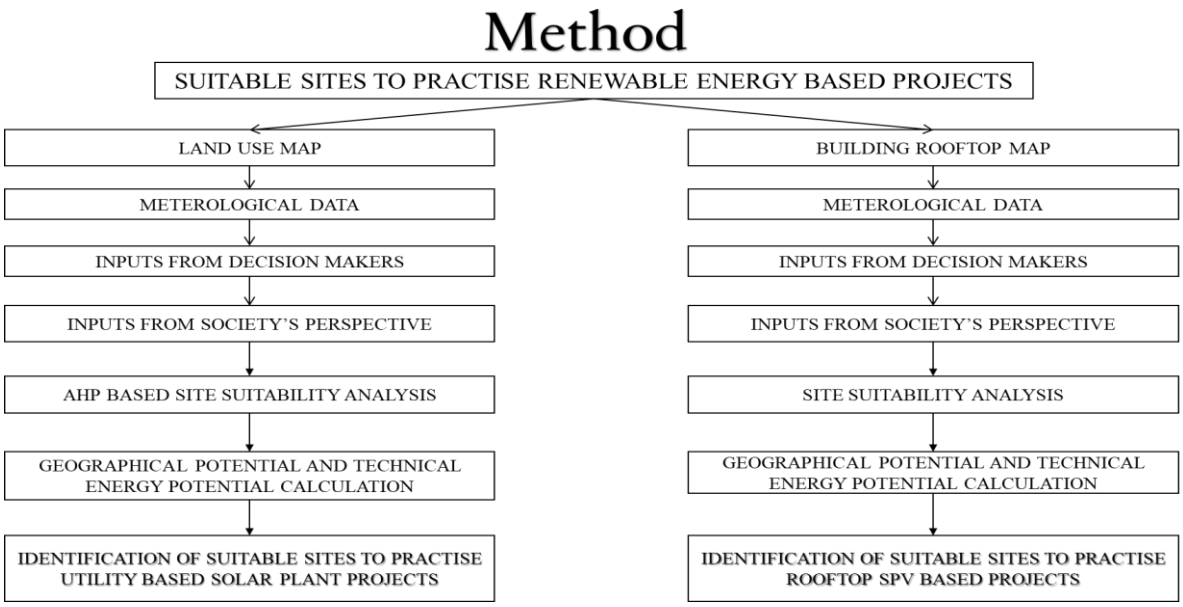
Method
SUITABLE SITES TO PRACTISE RENEWABLE ENERGY BASED PROJECTS
LAND USE MAP
METEROLOGICAL DATA
INPUTS FROM DECISION MAKERS
INPUTS FROM SOCIETY'S PERSPECTIVE
AHP BASED SITE SUITABILITY ANALYSIS
GEOGRAPHICAL POTENTIAL AND TECHNICAL ENERGY POTENTIAL CALCULATION
IDENTIFICATION OF SUITABLE SITES TO PRACTISE UTILITY BASED SOLAR PLANT PROJECTS
BUILDING ROOFTOP MAP
METEROLOGICAL DATA
INPUTS FROM DECISION MAKERS
INPUTS FROM SOCIETY'S PERSPECTIVE
SITE SUITABILITY ANALYSIS
GEOGRAPHICAL POTENTIAL AND TECHNICAL ENERGY POTENTIAL CALCULATION
IDENTIFICATION OF SUITABLE SITES TO PRACTISE ROOFTOP SPV BASED PROJECTS

Figure 3: Method followed for 3rd objective

As the city is mainly residential and industrial in nature, solar rooftop is a better option for solar energy generation within city premises. However, the primary survey suggests that the citizens are unwilling to adopt the new technology until the Government provides them with enough knowledge and incentives to construct and maintain the system. Further, they are more optimistic to consume green electricity if the energy is generated by the power generating companies. Therefore, the geographic and technical potential to generate solar energy from rooftops of Government buildings was also estimated. The building footprints of the Government building, buildings and trees surrounding it were digitized from google earth. The height of the buildings was measured and portion of rooftops intersecting with shadow of trees were eliminated. A shadow analysis was also performed to extract rooftop area suitable for solar planning. Geographical potential accounts for the total area available for setting up solar PV technology in the area of interest, and can be enumerated as given in equation:

$$G = A \times I \times H \qquad \text{eq1}$$

Where, A is the suitable area for PV installation (units in m^2), I is the average insolation on tilted panels (units in $kWh/m^2/day$), and H is the number of sunshine hours in a day (units in hours). The insolation value used for potential calculation of CSP is the average DNI value of Haora, as obtained from NASA database, i.e., 4.7 $kWh/m^2/day$. Similarly, in case of SPV, I value considered is 5.67 $kWh/m^2/day$, which is the average GHI value of Haora. The sunshine hours was calculated using r.sunhours module in GRASS GIS 7.0, where latitude, elevation, year, month and day for which the values are calculated are used as input to derive sun elevation and azimuth and eventually sunshine hours is mapped as a raster. H values derived for Haora are 10, 13, 11, and 10 hours used for January–March, April–June, July, September, and October–December respectively. In case of solar rooftops, NREL has aggregated the total percentage of area unsuitable for solar equipment installation due to other uses or has shading effects, and the range varies from 25% to 35% on an average (Melius et al., 2013). In this study, the total shading effect has been calculated, and subtracted from total rooftop area available. This

calculation was done only for Haora city as the energy Master plan of New Town city has already calculated the generation potential of solar energy for residential, commercial, industrial and Government buildings.

The technical electricity potential of CSPs (ECSP) is calculated by the equation as provided by Trieb (2009),

$$\mathrm{ECSP} = \mathrm{G} \times \text{Land use efficiency} \qquad \text{eq2}$$

Land-use efficiency is a function of land-use factor multiplied by solar to electric conversion efficiency. Land-use factor (LUF) is the total amount of area covered by the CSP system with respect to the total land present. Solar to electric conversion efficiency is the total DNI incident on the CSP receiver that can be converted to net electricity supplied to the grid. In the Indian context, a parabolic trough system was considered as the CSP reference system, thus the annual solar to electric conversion efficiency of 15% with LUF of 37% was used for calculating land-use efficiency (Ummadisingu & Soni, 2011).

The equation used to calculate technical electricity potential of SPVs (ESPV) of the rooftop solar PV as determined by Hoogwijk (2004) is as follows:

$$\mathrm{ESPV} = \mathrm{G} \times \mathrm{PR} \times \mathrm{r} \times \eta\mathrm{th} \qquad \text{eq3}$$

where PR stands for Performance ratio or the conversion efficiency of the inverter, including cabling losses, dust on the panels, and others. The value ranges between 0.5 and 0.9 (default value used = 0.75). r stands for efficiency of solar panel (range between 15 and 18% default value used = 15% (Charfi et al., 2018)) and ηth is temperature and irradiance losses (default value used = 0.9 (Bergamasco & Asinari, 2011)) from the system.

Findings and Discussion

Key drivers of solar city planning

With respect to the technical and economic feasibility, 50% of the cities have scored more than the average value. The reason can be attributed to their higher solar irradiation capturing capacity. Cities situated in North and West India, have a greater scope of capturing solar irradiation in comparison to the cities situated in South and East India. The value of the CSI ranges from 0.2 to 0.8. Cities like Leh, NDMC, and Chandigarh have performed better than most cities. The cities which have performed moderately or poorly because their performance in the indicators of transport facilities and social amenities provided by the city are less. This has hindered their overall performance, as they carry a greater weightage while computation of the index. Similarly, very few cities have a sustainable energy system. The reason for their higher sustainability is affordability and environment aspects. In these cities, the charges for the electricity connection for domestic and commercial sector is lesser than other cities and the cities like Indore, Bhopal, Howrah, Bhubaneswar have performed poorly because of their lower values in the social aspects of ESSI. These cities have seen fewer increase in the number of electricity connections over the decade. The Grey Relational Analysis was done combining the scores of the three sustainability indices. Here 50% of the cities have scored higher than the average score. The higher score is mainly attributed to a higher CSI and Technical and Economic Feasibility score, the cities which have performed moderately have a mixed score distributed on the three sustainability indices, while the cities which have performed poorly have a low score in all the three indices.

Importance of Local energy Master Plans in Solar City Planning

Eleven indicators were chosen, as derived from literatures, them being: Mission objectives and energy goals, City demographics and affordability, City morphology and Built-up area distribution, Energy Stocks and Flows, Operating cash flow and green finance, Financial benefits, Technical efficiency, Social outlook, Private sector participation, Environmental effectiveness and Public engagement. The

application of TISM model suggests that the most important enablers of local energy planning process for Solar City Mission should be Mission objectives and energy goals, followed by the second most important level which includes Stocks and flows, Environmental effectiveness and Operating cash flow and green finance. These four parameters are of utmost importance while planning Solar cities, designing energy plans and promoting energy efficient development of cities. The third level of parameters were City Demographics and affordability, City morphology and Built-up area distribution, Financial benefits, Private sector participation and Technical efficiency. The household affordability is an important criterion, however built up area distribution and city morphology is of secondary concern if the capital and technology is available. The experts have shown deep concern on job growth, net savings and awareness programs will be a help in reality as they have more knowledge about what happens in reality and therefore in ideal conditions, they should be a top enabler, however, in reality they are only in documentations but rarely achieved.

In the second stage, five cities, New Delhi Municipal Corporation (NDMC), Haora, Ludhiana, Bhubaneswar and New Town were visited, and a primary survey was conducted on the approach and willingness to invest in solar energy technology by the Municipality and their respective solar city cells in their city premise from the Solar City project scheme. It was observed that all the cities had started the solar city project, however, Howrah Municipal Corporation had halted the project due to lack of access to solar city fund as they lacked a master plan. The remaining Municipalities explained how different stakeholders had designed their master plan, considering population growth, energy consumption demand, and carbon emission rate. They also explained the importance of National Solar Mission, GRIHA and ECBC codes in facilitating them to implement these schemes on commercial and industrial buildings. The Municipalities of cities in Eastern India, as of now, prefer to invest in solar powered streetlights, traffic signals, and multilevel car parking. Ludhiana Municipal Corporation gives incentives to individuals and organizations for setting up solar panels, a method not preferred by the other cities as the frequency of solar panel usage is less in Haora and Bhubaneswar. In NDMC, most of the Government schools and few Government buildings have well maintained and functioning solar PVs installed in their rooftops, which are attached to a meter so that the amount of electricity generated in verified and documented by the operator periodically.

Society's approach towards solar energy adoption

A literature review on society's perspective on solar energy was conducted before going out for a field survey. In most success stories, the reason for installing solar rooftops is attributed to more savings, reduction in carbon footprint, ample supply during peak hours and consumer's long term reliability on power source. The cities of Punjab, Haryana and Rajasthan have solar panels in rooftops of not only public and commercial use but also on residential rooftops. They receive incentives from the Government to install solar panels, whose price per unit is deducted in the billing. However, in other states, although there are provisions where selling of electricity is permissible to the power utility grids, the DISCOMS consider this as a threat in future, therefore they either disapprove buying extra units of solar energy from domestic buildings or increase the minimum amount of energy to be generated by a household before selling, thus going against the system. This introduces weakness and threats in the system. However, only when a household looks into the solar technology system as a cultural change brought by technological change, sense of ownership of a new technology to power independent connections at home, specially cameras, emergency lights and fans instead of using inverter, and contribute to reducing carbon footprint, or in places where there is frequent power cuts during peak hours, those situations provide the opportunities in Indian society to accept a new cost intensive technology. India's solar energy deployment goals cannot be met by large-scale projects alone as land becomes a scarce commodity. Rooftop solar is an obvious choice in a country with severe transmission issues. Nonetheless it is necessary to learn whether the inhabitants of a city are willing to install a cost-intensive but good returns technology in their household. Therefore, a primary survey was conducted in Haora city to understand whether the inhabitants are willing to invest in solar technology. Stratified random sampling method was used to survey 150 residents of the city.

The primary survey reports that although 90% of the respondents feel *strongly* determined to make positive contribution in the society in terms of environment protection, reduction of fossil fuel

consumption and consuming green electricity supplied by the DISCOM, they *disagree* to adopt solar rooftop technology in their households. The reason stated by the respondents include unawareness of the technology and satisfaction with the current source of electricity supply. Around 80% of the respondents use energy efficient bulbs (LED / CFL) at their home and feel that they have *very often* reduced fuel or energy consumption at home due to environmental reason. Around 30% of the respondents are aware of their local governing bodies are taking initiatives to convert your city to a solar city.

Delineation of suitable sites for promoting solar energy projects

The assessment of solar power potential at both macro and micro scales is significant for stakeholders to ascertain feasible geographical locations with abundant and consistent natural resources. The initial study on benefits of energy master plans of cities have explained the importance of a guidebook for stakeholders to fulfil SCM in their respective cities, thereby prompting a need to delineate suitable sites to construct solar energy related projects in a city where the energy master plan has not been compiled. Haora city in one of such cities which does not have an energy master plan. While the Municipal Corporation (HMC) is eager to experiment this revolutionary technology within its city premises, the citizens are not comfortable in relying on domestic solar rooftop connections solely for power generation and consumption. Hence, small scale utility solar parks in the vicinity of the city established by the Government, and solar power generation from rooftops of Government buildings is the immediate and most suitable solution for solar city planning in Haora Municipal Corporation. Similarly, an energy master plan to fulfil the SCM objectives has already been drafted and sanctioned by the New Town Kolkata Development Authority, which states the potential sites and their electricity generation capacity on building rooftops of New Town. Thus, potential sites for small scale utility plants have been delineated in this study in order to identify zones which can be used to generate large scale solar energy.

The weighted overlay analysis was performed to derive the suitable locations for solar infrastructure deployment in the form of CSPs in New Town and Haora city. The solar site suitability map as generated by the weighted overlay analysis is presented in Figure 4 and Figure 5 along with the AHP results in table 3. The Consistency Ratio of the analysis was calculated to check the sensitivity of the analysis and a value of 0.051 was recorded. The observation describes that the expert opinions and weights derived are consistent in nature. The weights of the different criterions for solar farm suitability planning are summarised as follows:

Table 3: Weights derived from AHP analysis

Criteria	Solar irradiation	LST	Slope	Distance from power transmission lines	Distance from roads	Land Use
Weights	0.34	0.27	0.13	0.09	0.09	0.08

A city with an energy master plan: New Town

The weighted overlay analysis was performed to derive the suitable locations for solar infrastructure deployment in the form of CSPs in New Town, Kolkata. The suitable zones, ranging from the worst to the best, can be observed in Figure 4. As observed, a very small area of 0.467 km^2 is selected as the most suitable location for solar farm planning in New Town. This is followed by the moderately suitable sites for implementing this project and comprises 19.20 km^2 of the total area. These regions, as depicted in figure 4, are mainly the canals and the vacant and agricultural lands. The canals are suitable for solar farm space allocation planning as per the experts and the same is reflected in the suitability distribution map. These zones might be more profitable than the other suitable sites for constructing solar plants mounted on canals or small solar farms on agricultural lands. According to the classification, the suitable zones occupied a striking amount of area of the city, which sums upto around 15.6 km^2. The vacant lands and parts of cultivable lands constitute the moderately suitable zones of the suitability analysis. The area falling under this zone has the probability to harness solar energy efficiently through

smart investment in solar technology. The second last category occupies the least area in the suitability distribution map. The less suitable zone occupied around 0.256 km^2 of the study area, mainly consisting of roads, an urban green zone, and residential and commercial areas. Finally, the unsuitable zone, as mapped in the suitability distribution map, occupies around 25.9 km^2 of the study area and is scattered throughout the study area. These regions are situated beside prohibited zones and have the least solar irradiation, higher slope values, and are faraway from road and transmission lines. Therefore, they are highly unsuitable for investments in solar technology in these areas.

Table 4: Geographical potential (kWh) and technical electricity generation potential of CSPs (in MWh) under ideal conditions of solar systems

Zones	Highly suitable		Moderately suitable		Suitable	
Area (in km^2)	0.4671		19.2022		15.5720	
Months	G	ECSP	G	ECSP	G	ECSP
JAN to MAR	914737.5000	50.7679	37604308.3333	2087.0391	30495166.6667	1692.4818
APR to JUN	1189158.7500	65.9983	48885600.8333	2713.1508	39643716.6667	2200.2263
JUL to SEP	1006211.2500	55.8447	41364739.1667	2295.7430	33544683.3333	1861.7299
OCT to DEC	914737.5000	50.7679	37604308.3333	2087.0391	30495166.6667	1692.4818

G is represented in kWh (Here the unit of A used to calculate G is m^2) and ECSP is represented in MWh

A city without an energy master plan: Haora

As observed in Figure 5, a very small area of 0.073 km^2 is computed as the most suitable location for solar farm planning in Haora city. This is followed by the suitable sites for implementing this project and comprises 0.8 km^2 of the total area. These regions, as depicted in figure 5, are mainly the harvested fallow lands and the cultivable lands. This expanse is under both Government and private holdings and therefore the planning of CSPs need more supervised planning. The geographical potential and technical electricity potential of CSPs was calculated for each category. The results are presented in table 5.

Table 5: Geographical potential (kWh) and technical electricity generation potential of CSPs (in MWh) under ideal conditions of solar systems

Zones	Highly suitable		Moderately suitable		Suitable	
Area (in km^2)	0.0731		0.8641		13.02798	
Months	G	ECSP	G	ECSP	G	ECSP
JAN to MAR	143242.2917	7.9499	1692387.7500	93.9275	25513137.2917	1415.9791
APR to JUN	186214.9792	10.3349	2200104.0750	122.1058	33167078.4792	1840.7729
JUL to SEP	157566.5208	8.7449	1861626.5250	103.3203	28064451.0208	1557.5770
OCT to DEC	143242.2917	7.9499	1692387.7500	93.9275	25513137.2917	1415.9791

G is represented in kWh (Here the unit of A used to calculate G is m^2) and ECSP is represented in MWh

Similarly, after the elimination of shadow area falling on individual Government building, the total available rooftop area was calculated for January–March, April–June, July, September, and October–December. Thereafter, the geographical potential and technical electricity potential of SPVs for each season was calculated using the equation 1 and 3 and is reported in table 5.

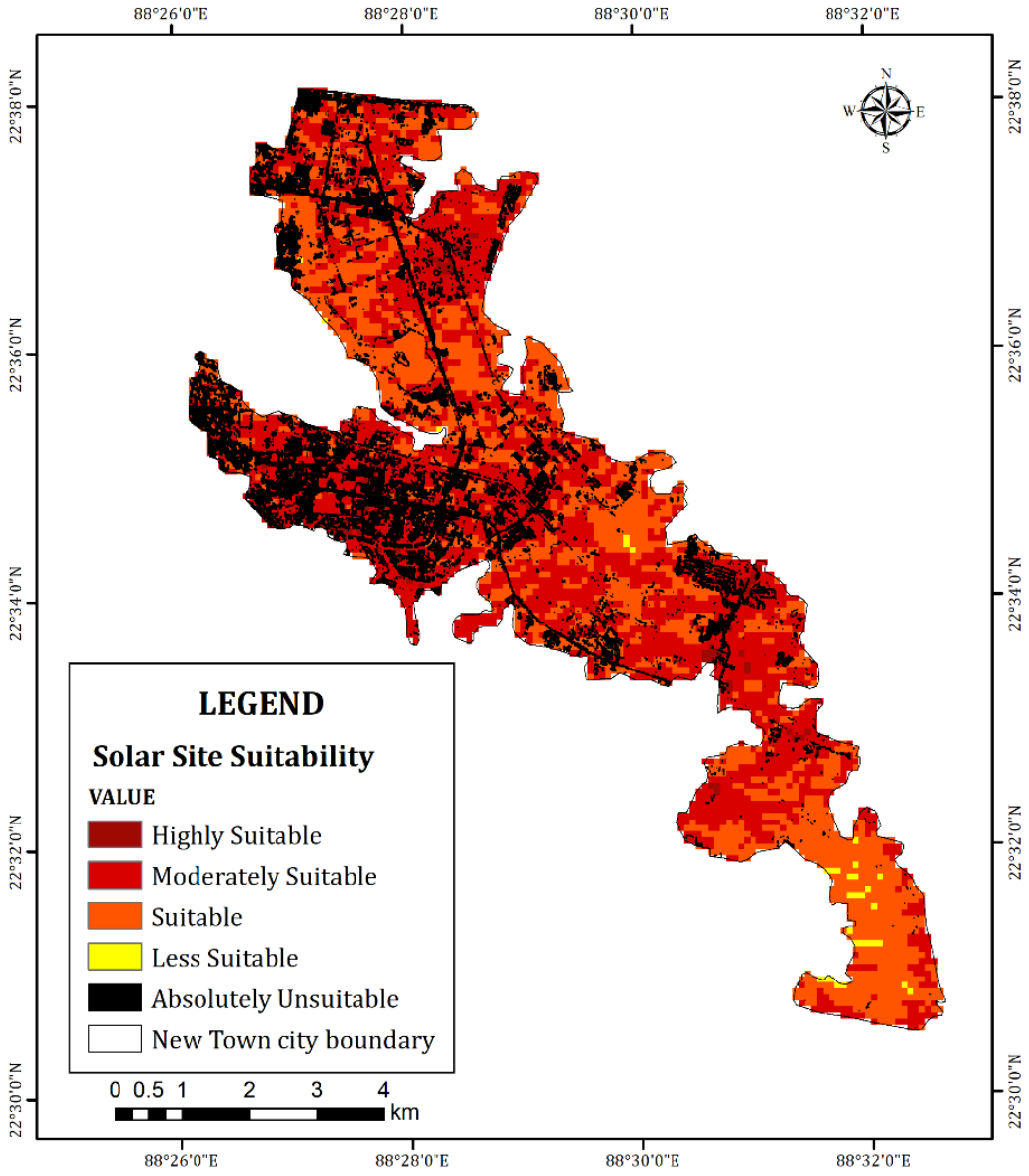

Figure 4: Solar Site Suitability Map for utility scale plants in New Town city

Table 6: Geographical potential (kWh) and technical electricity generation potential of SPVs (in MWh) under ideal conditions of solar systems

Months	Total Rooftop Area (km^2)	Shadow area (km^2)	Suitable Rooftop Area (km^2)	G	ESPV
JAN to MAR	0.1233	0.0033	0.1200	283491.4054	28.7035
APR to JUN	0.1233	0.0018	0.1215	373293.7784	37.7960
JUL to SEP	0.1233	0.0033	0.1200	311912.9873	31.5812
OCT to DEC	0.1233	0.0556	0.0677	159976.3036	16.1976

G is represented in kWh (Here the unit of A used to calculate G is m^2) and ECSP is represented in MWh

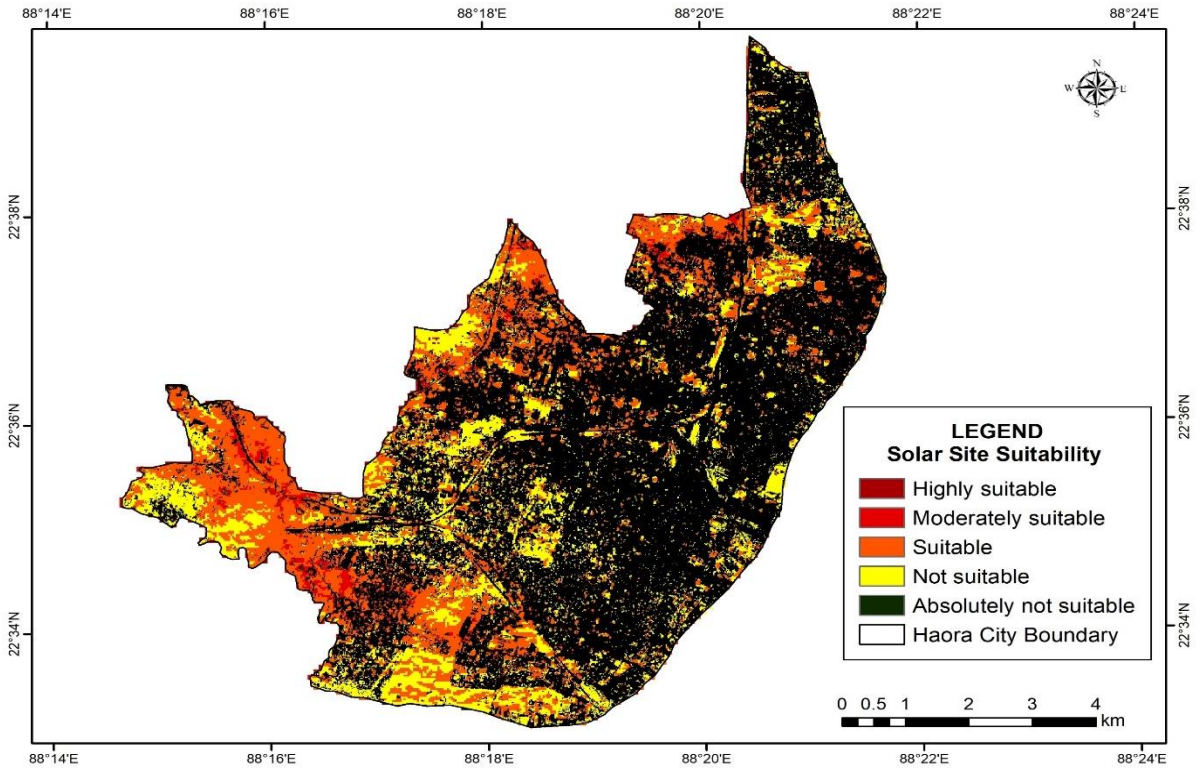

Figure 5: Solar Site Suitability Map for utility scale plants in Haora city

The geographical potential of the building rooftops varies significantly between summer and winter months, with the least potential recorded between October and December. The summer months have higher geographical potential to tap solar energy from rooftop PVs, and the slight difference measured in July-September span can be attributed to the solar inclination during those months and the presence of cloud cover. Similar pattern is noticed in the technical electricity generation potential of rooftop PVs, as the values are directly proportional to the geographical potential values. However, such performance still ensures a minimum generation of 16 MWh within the Government building rooftops in the winter season, amidst ideal conditions.

Chapterization

This thesis is divided into 9 chapters. The first chapter introduces my research work, its motivation, and the research question, while the second chapter lists the literatures reviewed regarding my research topic, discussing about solar cities planning policies, what factors contribute to its fast development and how suitable sites can be delineated using remotely sensed data to establish renewable energy based projects in cities. The third chapter is about the Study Area, and the fourth chapter gives a detailed information about the datasets and method used in the study. The fifth chapter explains the key drivers of solar city planning, revolving around the detailed description of the findings from the first objective. In the sixth chapter, the detailed findings and analysis of the 2nd objective is discussed. Firstly, an analysis on which indicators are important for Solar City Planning was evaluated and finally, the ground truth of application of local energy plans in various municipalities was discussed. In the seventh chapter, society's approach towards solar energy adoption in the final city of concern was evaluated. Finally, in the eight chapter, a detailed findings and analysis of suitable locations where solar PVs or small utility scale solar plants can be set-up in New Town and Haora city was discussed. The thesis ends with the ninth chapter, which provides a summary of the entire research in the Conclusion chapter.

Conclusion

This study opens new horizons for spatial awareness from freely available data sources of solar energy resources, and thus examines the viability of technoeconomic potential of solar energy resources, the city's potential to adopt the advanced technology and the sustainability quotient of the power utility

companies in different solar cities of India as a means to assess the viability of the Solar Cities Mission program in all these cities. Here, for the first time, a multivariate approach to exploring the feasibility of solar cities using the TOPSIS-GRA approach was conducted to study the spatial allocation of solar energy resources all over India. The cities located in the west and south India have the highest potential to tap solar energy in the form of SPVs and CSPs and, therefore, maximum investment should be directed in electrifying these cities from solar energy. The National Solar Mission and the SCM are smart initiatives by the Indian government to mandate the use of renewable energy in the Indian cities.

Government interventions and incentives are the traditional forms to promote usage of renewable energy and energy efficiency measures at both national and local level. The hindrances that prevent such developments are inconsistency in resource allocation, capital, and inclusive decision-making among the stakeholders. In retrospect, the stakeholders should analyse the potentiality of a region before investing in solar energy systems. The study provides an initial overview of SCM's success rate based on its objectives, i.e. to promote the consumption of renewable energy and utilise energy-efficient technologies in urban areas of India. The TOPSIS method was used to benchmarks cities depending on the natural endowments they possess for successful implementation of SCM. It was observed that cities like Leh, Amritsar, Jodhpur, Gandhinagar, Surat, Rajkot, Indore, Bhopal, Nagpur, Aurangabad, Bilaspur and Raipur have the highest potential to disseminate solar energy technologies. They have also performed better in the ESSI, and therefore, there is a scope of future large-scale investments and guaranteed profits in these cities. The cities like Vijayawada, Mahbubnagar, Panaji, Bhubaneswar, Surat, Hubli-Dharwad, Mysore, Coimbatore, Thiruvananthapuram and Kochi have performed moderately and can expect good returns from a long-term investment. On the contrary, cities of north-east India and east India have performed poorly and proper investigation into solar markets and consumer's willingness-to-pay is a priori for future solar investments. Mission objectives, energy governance, energy modelling and future projections are the fundamental driving factors for planning bodies and stakeholders to implement energy master plans successfully. The total demand of the city, the proportion of energy production from renewable energy, total energy imports, availability of capital for investment and economic resilience of the investing organization to supply capital throughout the project also helps in sustaining such ambitious Missions for years. Additionally, the assessment of delineating suitable sites for small scale utility solar parks and solar rooftops in Government buildings has helped in determining whether the city is ready to adopt the challenging and revolutionary technology or not. Thus, the attempt to decarbonize the power sector is essential for energy efficient cities and future conversion to a smart city. The employment of smart grid technology, energy-efficient technologies, and the utilization of renewable energy sources to generate power can meet local energy demands and assists as a clean solution to protect the environmental. A gradual shift to renewable energy is mandatory for India to secure citizens from the perils of climate change and global warming.

References

Amado, M. P., & Poggi, F. (2013). *Planning for Solar Smart Cities*.

Athanassiadis, A., Fernandez, G., Meirelles, J., Meinherz, F., Hoekman, P., & Cari, Y. B. (2017). Exploring the energy use drivers of 10 cities at microscale level. *Energy Procedia*, *122*, 709–714. https://doi.org/https://doi.org/10.1016/j.egypro.2017.07.374

Bagheri, M., Delbari, S. H., Pakzadmanesh, M., & Kennedy, C. A. (2019). City-integrated renewable energy design for low-carbon and climate-resilient communities. *Applied Energy*, *239*, 1212–1225.

Balocco, C., & Grazzini, G. (2000). Thermodynamic parameters for energy sustainability of urban areas. *Solar Energy*, *69*(4), 351–356.

Bergamasco, L., & Asinari, P. (2011). Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: Application to Piedmont Region (Italy). *Solar Energy*, *85*(5), 1041–1055.

CEA. (2021). *Monthly Renewable Energy Generation Report 2021*. https://cea.nic.in/wp-content/uploads/resd/2021/01/Broad overview Jan 2021 .pdf

Charfi, W., Chaabane, M., Mhiri, H., & Bournot, P. (2018). Performance evaluation of a solar photovoltaic system. *Energy Reports*, *4*, 400–406.

Cheng, V., Steemers, K., Montavon, M., & Compagnon, R. (2006). Urban form, density and solar potential. *PLEA 2006, LESO-PB-CONF-2006-008*.

de Oliveira, E. M., & Oliveira, F. L. C. (2018). Forecasting mid-long term electric energy consumption through bagging ARIMA and exponential smoothing methods. *Energy*, *144*, 776–788.

Dias, R. A., Mattos, C. R., & Balestieri, J. A. P. (2006). The limits of human development and the use of energy and natural resources. *Energy Policy*, *34*(9), 1026–1031.

Dincer, I., & Rosen, M. A. (2005). Thermodynamic aspects of renewables and sustainable development. *Renewable and Sustainable Energy Reviews*, *9*(2), 169–189.

Fadare, D. A. (2009). Modelling of solar energy potential in Nigeria using an artificial neural network model. *Applied Energy*, *86*(9), 1410–1422.

Girish, B. M., Siddesh, H. S., & Satish, B. M. (2019). Taguchi grey relational analysis for parametric optimization of severe plastic deformation process. *SN Applied Sciences*, *1*(8), 937. https://doi.org/10.1007/s42452-019-0982-6

Hoogwijk, M. M. (2004). *On the global and regional potential of renewable energy sources*.

Hwang, C.-L., & Yoon, K. (1981). Methods for multiple attribute decision making. In *Multiple attribute decision making* (pp. 58–191). Springer.

Kammen, D. M., & Sunter, D. A. (2016). City-integrated renewable energy for urban sustainability. *Science*, *352*(6288), 922–928.

Kennedy, C. A., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., Uda, M., Kansal, A., Chiu, A., Kim, K., Dubeux, C., Lebre La Rovere, E., Cunha, B., Pincetl, S., Keirstead, J., Barles, S., Pusaka, S., Gunawan, J., Adegbile, M., … Sahin, A. D. (2015). Energy and material flows of megacities. *Proceedings of the National Academy of Sciences*, *112*(19), 5985 LP – 5990. https://doi.org/10.1073/pnas.1504315112

Liu, J., Chen, X., Cao, S., & Yang, H. (2019). Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings. *Energy Conversion and Management*, *187*, 103–121.

Martinez, D. M., & Ebenhack, B. W. (2008). Understanding the role of energy consumption in human development through the use of saturation phenomena. *Energy Policy*, *36*(4), 1430–1435.

Melius, J., Margolis, R., & Ong, S. (2013). *Estimating rooftop suitability for PV: a review of methods, patents, and validation techniques*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Mitra, A. P., Sharma, C., & Ajero, M. A. Y. (2003). *Energy and Emissions in South Asian Mega-cities : Study on Kolkata , Delhi and Manila*. *February 2003*, 4–5.

MNRE. (2015). *Solar / Green Cities*. https://mnre.gov.in/solar-cities

MNRE. (2022). *Solar Energy Overview*. https://mnre.gov.in/solar/current-status/

Muñoz, F. D., Suazo-Martínez, C., Pereira, E., & Moreno, R. (2021). Electricity market design for low-carbon and flexible systems: Room for improvement in Chile. *Energy Policy*, *148*, 111997.

Pachauri, S., & Jiang, L. (2008). The household energy transition in India and China. *Energy Policy*, *36*(11), 4022–4035.

PIB. (2018). *A target of installing 175 GW of renewable energy capacity by the year 2022 has been set*. Ministry of New and Renewable Energy. http://pib.nic.in/newsite/PrintRelease.aspx?relid=180728

Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. *Energy and Buildings*, *37*(7), 762–776.

Reddy Sudhakara, B., & Balachandra, P. (2003). Integrated energy-environment-policy analysis. *Utilities Policy*, *11*(2), 59–73.

Satterthwaite, D. (2009). The implications of population growth and urbanization for climate change. *Environment and Urbanization*, *21*(2), 545–567.

Schmidt, J., Cancella, R., & Pereira Jr, A. O. (2016). An optimal mix of solar PV, wind and hydro power for a low-carbon electricity supply in Brazil. *Renewable Energy*, *85*, 137–147.

Steemers, K. (2003). Energy and the city: density, buildings and transport. *Energy and Buildings*, *35*(1), 3–14.

Trieb, F. (2009). Global potential of concentrating solar power. *Conference Proceedings*.

Tripathi, L., Mishra, A. K., Dubey, A. K., Tripathi, C. B., & Baredar, P. (2016). Renewable energy: An overview on its contribution in current energy scenario of India. *Renewable and Sustainable Energy Reviews*, *60*, 226–233.

Ummadisingu, A., & Soni, M. S. (2011). Concentrating solar power–technology, potential and policy in India. *Renewable and Sustainable Energy Reviews*, *15*(9), 5169–5175.

Vossier, A., Zeitouny, J., Katz, E. A., Dollet, A., Flamant, G., & Gordon, J. M. (2018). Performance bounds and perspective for hybrid solar photovoltaic/thermal electricity-generation strategies. *Sustainable Energy & Fuels*, *2*(9), 2060–2067.

Wang, B., Cot, L. D., Adolphe, L., Geoffroy, S., & Sun, S. (2017). Cross indicator analysis between wind energy potential and urban morphology. *Renewable Energy*, *113*, 989–1006.

Wang, S., Fang, C., & Wang, Y. (2016). Spatiotemporal variations of energy-related CO2 emissions in China and its influencing factors: An empirical analysis based on provincial panel data. *Renewable and Sustainable Energy Reviews*, *55*, 505–515.